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Experimental Assessment of Gradient Plasticity

Monica M. Barney, Geoffrey H. Campbell, James S. Stölken, Adam J. Schwartz, Jürgen M. Plitzko, Wayne E. King, and J. W. Morris, Jr.*

Chemistry and Materials Science Directorate, University of California, Lawrence Livermore National Laboratory P.O. Box 808, Livermore, CA 94550
**Materials Sciences Division, Ernest Orlando Lawrence Berkeley National Laboratory, One Cyclotron Road, MS 66, Berkeley, CA 94720*

ABSTRACT

Classical plasticity theories generally assume that the stress at a point is a function of strain at that point only. However, when gradients in strain become significant, this localization assumption is no longer valid. A common factor in the failure of these conventional models is that, since they do not account for the strain gradients, they do not display a size effect. This effect is seen experimentally when the scale of the phenomenon of interest is on the order of several microns. At this scale, strain gradients are of a significant magnitude as compared to the overall strain and must be considered for models to accurately capture observed phenomena.

The mechanics community has been actively involved in the development of strain gradient theories for many years. Recently, interest in this area has been rekindled and several new approaches have appeared in the literature. Two different approaches are currently being evaluated: one approach considers strain gradients as internal variables which do not introduce work conjugate higher order stresses, and another approach considers the strain gradients as internal degrees of freedom which requires work conjugate higher order stresses. Experiments are being performed to determine which approach models material behavior accurately with the least amount of complexity. One difference between the two models considered here is the nature of the imposed boundary conditions at material interfaces. Therefore, we are investigating the deformation behavior of aluminum/sapphire interfaces loaded under simple shear. Samples are fabricated using ultra-high vacuum diffusion bonding. To determine the lattice rotations near the boundary, we are examining the samples with both electron backscatter diffraction methods (EBSD) in the scanning electron microscope and with different diffraction techniques in the transmission electron microscope. The experimentally found boundary conditions will be subsequently used to determine whether the simpler internal variable model is adequately descriptive or if the greater complexity associated with the internal degree of freedom approach may be necessary.

I. INTRODUCTION

Although not predicted by classical models, an increase in flow stress is seen during deformation when the relevant material length scale is on the order of a micron and inhomogeneties are present. For example, Fleck et.al (1993) showed that when loaded in torsion, a wire displays greater strength for smaller radii. Others authors have discussed this type of effect in other systems, including bending, indentation hardness, crack tip plasticity, particle hardened alloys, and polycrystalline samples. The increase in hardness under these conditions is due to additional dislocations needed for compatibility. These dislocations are commonly referred to as geometrically necessary dislocations (GNDs). The presence of the GNDs can be ignored and continuum theories applied at large size scales since gradients in strain are small. However, as the relevant material length scale approaches the wavelength of the deformation field, more dislocations are formed in a smaller area to accommodate the large strain gradient, resulting in higher stresses. This effect is not captured in continuum models because these models assume that the stress at a point is a function of strain at the same point only. When gradients in strain become significant, this localization assumption is no longer valid. This must be accounted for in a non-local theory to accurately reflect material response. Two distinct classes of models that extend classical theories to include strain gradient effects are currently being evaluated. Fleck and Hutchinson (1993) have developed one approach in which strain gradients are included in the work function. This type of formulation considers strain gradients as internal degrees of freedom and requires work conjugate higher order stresses, which need additional boundary conditions. Acharya and Bassani (1996) have developed another approach in which a strain gradient term is included in the hardening function. In this method, the strain gradients are considered to be internal variables, which do not introduce work conjugate higher order stresses or additional boundary conditions. This approach has the advantages that it is simpler overall, preserves the structure of the classical boundary value problem, and can easily be implemented into existing finite element codes. However, the additional boundary conditions in the higher order theory allow for the presence of a boundary layer. Specifically, Fleck and Hutchinson (1993) determined theoretically that a boundary layer of lattice rotation would be presence at an interface between dissimilar materials loaded under remote simple shear. Boundary layers seem likely in real materials, since dislocation motion is governed by stress fields that are strongly affected by boundaries (Wikström (2000)). The presence of a boundary layer, however, has not yet been determined definitively. Although previous experimental work by Sun et.al (1998) suggests the presence of a boundary layer, the data is difficult to interpret due to the interaction of the dislocations with the grain boundary. Determining the actual deformation behavior at interfaces would supply critical information in the continued development of strain gradient plasticity theories. Therefore, experiments performed at a metal-ceramic interface are proposed to determine deformation behavior without the complication of dislocation-grain boundary interactions.

II. EXPERIMENTAL WORK

Samples have been designed to study the deformation behavior at a metal-ceramic interface. The samples consist of a metal foil sandwiched between two polished ceramic cylinders. C-axis oriented sapphire polished to $\lambda/10$ flatness as obtained from General Ruby & Sapphire was used for the ceramic. Aluminum was chosen for the metal because of its relatively simple deformation behavior as compared with other available choices. 99.999% pure aluminum foils are obtained from Metron Company. An ultra-high vacuum diffusion-bonding machine (King et al) is used to bond the sapphire cylinders to the aluminum foil. The aluminum foils are 25-50 microns thick and the sapphire rods measure 16 mm in diameter and 20 mm tall. Prior to bonding, the surfaces are cleaned by sputtering and characterized by Auger spectroscopy. The samples are held at 600°C for 38 hours with an applied pressure of 10MPa. To determine the strength of the aluminum-sapphire bond, a notch is cut in the aluminum and symmetric 4-point bend tests are performed. Fracture surfaces have the dimpled morphology characteristic of ductile fracture, indicating that failure occurs in the aluminum and not at the interface. This shows that the aluminum is strongly bonded to the sapphire and is assumed to deform before debonding in this study.

In order to shed light on existing strain gradient models, a simple shear stress state is needed for testing. This is because all models predict length scale effects to occur during inhomogeneous deformation modes. This stress state can be accomplished by testing the samples under *asymmetric* 4-point bending. A schematic illustration of the test geometry is shown in Figure 1. A constant amount of shear is present between the inner contact pins, but it is only directly underneath the load-point that there is no bending moment (Hognestad and Hills (1994)). Therefore, proper alignment of the interface underneath the load-point is essential to avoid mixed-mode loading. To prepare for testing, the cylindrical sandwiched samples are cut into rectangular rods that are approximately 40 mm long, 2.5 mm high, and 3 mm wide. The top and bottom are ground flat for ease of mechanical testing and polished to 1μm to remove surface flaws that would lead to premature fracture of the sapphire. A bending test apparatus has been made for use in an Instron mechanical test frame. The test apparatus is designed to be self-aligning, so that the load from the mechanical test frame is transmitted directly onto the center of the bending apparatus. A 5kN-load cell is used to measure the force, and displacement is measured by an LVDT as well as by a feeler gauge placed underneath one side of the interface. The load-displacement curve for the mechanical test is shown in Figure 2.

The surfaces of the samples are observed using a scanning electron microscope (SEM) and displacement between the sapphire rods is observed. The displacement within the aluminum appears to be non-uniform. An average value of 48 ± 3μm of displacement has been determined by confocal optical microscopy. Undeformed samples are also scanned to ensure the accuracy of this method. These scans show that displacements between the sapphire were not present before testing.

In order to detect the presence of a boundary layer in the aluminum near the sapphire, the lattice rotations need to be measured from the center of the aluminum layer to the interface. To measure the rotation, electron backscatter diffraction patterns (EBSD) were generated in a SEM on these samples (see B.L. Adams, et. al (1993) for a description of EBSD). However, the signal was too weak to get accurate data under current sample preparation methods. Instead, the mechanically tested samples were cut into slices for observation in a transmission electron microscope (TEM). Lattice rotation can be measured using selected area electron diffraction patterns that display both Kikuchi lines as well as diffraction spots. The type of rotation in the diffraction pattern depends on which way the rotation is occurring in the lattice. Depending on the axis of rotation, either the lines will move with respect to the spots or the whole pattern will rotate with respect to the center. Either rotation can be measured with a precision of one degree. Unfortunately, standard TEM sample preparation methods cause the aluminum to recrystallize. Alternate sample preparation methods were employed, and an unrecrystallized sample was made out of an undeformed bar. Undeformed samples will be used to establish a baseline trend in lattice rotation. Deformed samples are currently being prepared in this newly established method to avoid recrystallization complications.

III. FUTURE WORK

The baseline trend in the undeformed samples will be fully characterized. Once deformed samples have been successfully prepared, lattice rotations will be measured using selected area diffraction in the TEM. Diffraction patterns will be used to determine the trend of lattice rotation as the interface is approached. The trends in rotation will be confirmed using EBSD in the SEM once improved sample preparation techniques are found that will allow for a stronger signal. Also, samples using single crystal metal layers will be fabricated. Copper will be used since it is easier to polish for diffusion bonding as well as TEM sample prep. It should also produce a stronger signal for EBSD since copper generates more backscattered electrons that aluminum. Single crystal aluminum may be used later if necessary.

IV. CONCLUSIONS

We are currently evaluating two models of strain gradient plasticity. They differ from one another in their levels of complexity and concomitant computational demands. The comparison with experimentally observed deformation boundary layers at interfaces should allow for an evaluation of the level of complexity that is necessary to capture relevant materials behavior in simulations.

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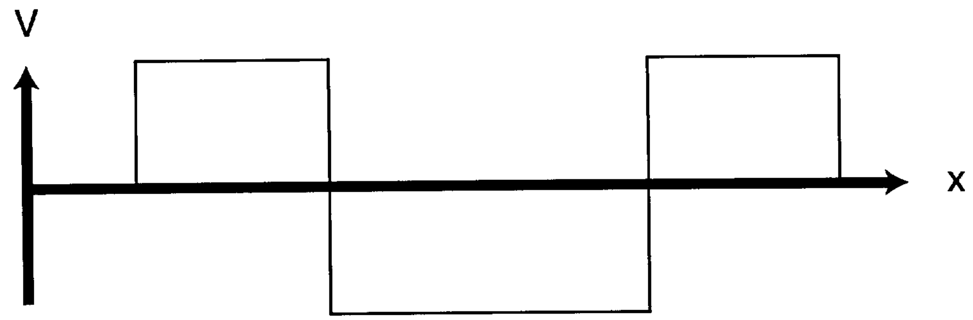
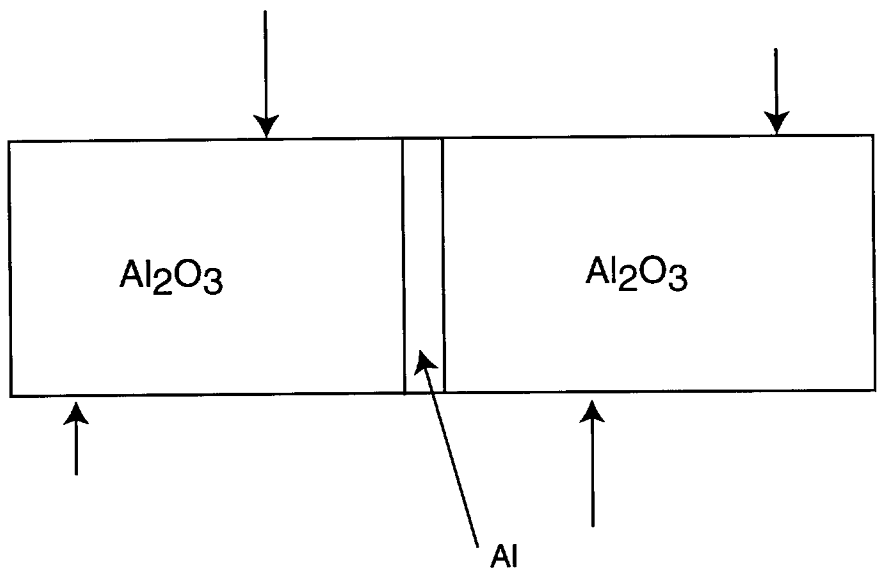
Shear Diagram





Moment Diagram

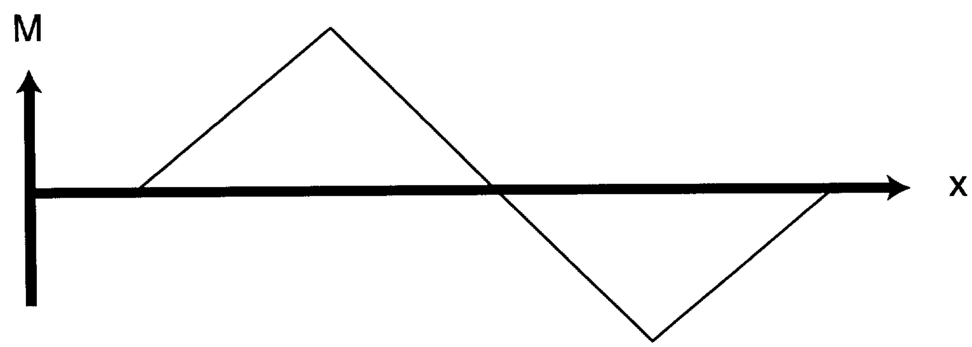
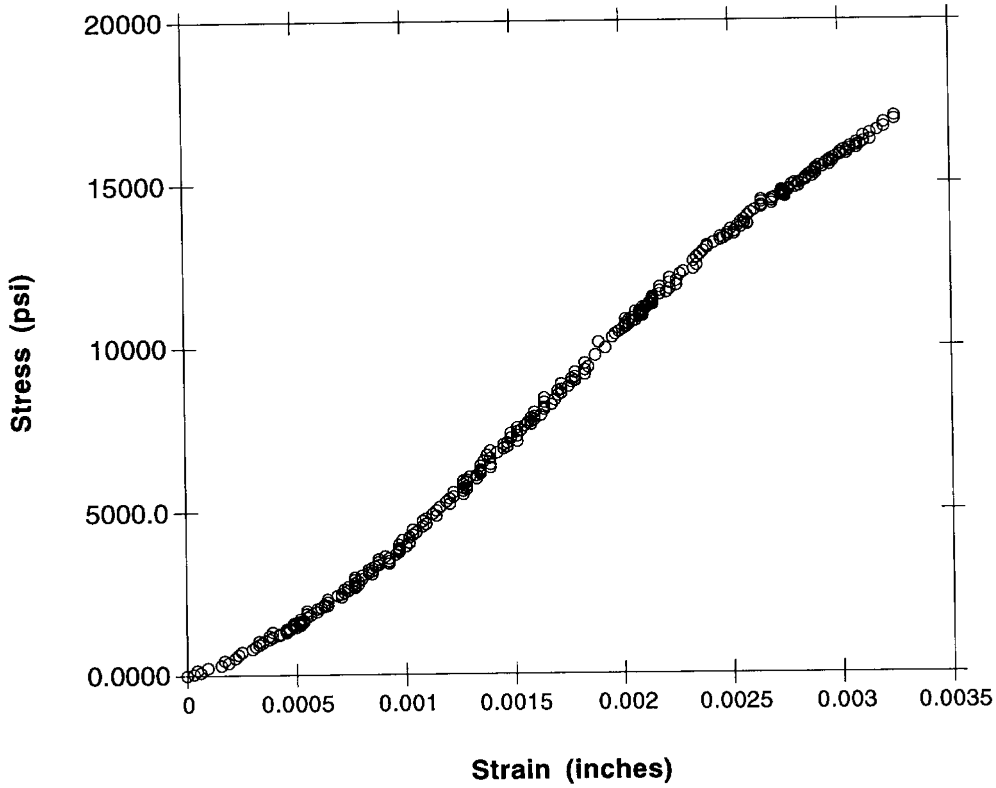


Figure 2



20000
15000
10000
5000.0
0.0000
Stress (psi)
0
0.0005
0.001
0.0015
0.002
0.0025
0.003
0.0035
Strain (inches)

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